

The companion properties of SNe Ia from the single degenerate model

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Abstract

Although Type Ia supernovae (SNe Ia) play very important roles in many astrophysical fields, the exact nature of the progenitors of SNe Ia is still unclear. At present, the single degenerate (SD) model is a very likely one. Following the comprehensive SD model developed by Meng & Yang (2010), we show the properties of SNe Ia companions at the moment of the supernova explosion. The results may provide help in searching for companion stars in supernova remnants. We compared our results with the companion candidate Tycho G of Tycho's supernova and found that integral properties of the star (mass, space velocity, radius, luminosity and effective temperature) are all consistent with those predicted from our SD model with the exception of the rotational velocity. If Tycho G was the companion star of Tycho's supernova, an interaction between supernova ejecta and the rotational companion might be a key factor to solve the confliction, and then it could be encouraged to do a detailed numerical simulation about the interaction.

Key Words: binaries: close, stars: evolution, supernovae: general, white dwarfs

1 Introduction

As wonderful distance indicators, Type Ia supernovae (SNe Ia) play an important role in cosmology and have been used successfully to determine cosmological parameters, resulting in the discovery of the accelerating expansion of the Universe [1,2]. However, the exact nature of SNe Ia progenitors is still unclear, especially the progenitor system [3,4]. Regarding the nature of the mass accreting WD companions, two competing scenarios have been proposed: the double-degenerate (DD, [5]) and the single degenerate (SD, [6,7]) channel. The DD model involves the merger of two CO WDs having a total mass larger than the Chandrasekhar (Ch) mass limit [8,9]. In the SD model, the maximum stable mass of the CO WD is $\sim 1.378M_{\odot}$ (close to the Ch mass limit [7]), and the companion is either a main sequence (or a slightly evolved) star (WD+MS, [10-14]), or a red-giant star (WD+RG, [15]) or a He star (WD + He star, [16]). This scenario is supported by many observations [17] and has been widely studied by many groups [18-24].

A direct way to confirm the progenitor model is to search for the companion stars of SNe Ia in their remnants since they can survive in the SD model but the entire system is destroyed after supernova explosion in the DD system. The discovery of the potential companion (Tycho G named by Ruiz-Lapuente et al. [25]) to Tycho's supernova has verified the power of the method, and also

the reliability of the SD model. Recently, the chemical abundances analysis of Tycho G by González-Hernández [26] supported the findings of Ruiz-Lapuente et al. However, the observed rotational velocity of Tycho G is not consistent with predictions from an analytic theory. Predictions suggest that Tycho’s supernova companion should have a high rotation rate but the observed rotational velocity is as low as 7.5 km s^{-1} [27]. It is therefore necessary to calculate the properties of the companion stars from the SD model, which may be helpful in finding the companions in supernova remnant, and compare them with the observed properties of Tycho G to see if the predictions match observations. Actually, some works has been done in this area [18,20,21,28], but has been based on the WD+MS channel. In this paper, the properties of the companion predicted in the WD+RG channel are considered since this channel is dominant in early type galaxies. As a result, our study should contribute to a more complete picture of the SN Ia.

The paper is a following-up to our previous paper[29] and our binary evolution calculation methods are similar to before(please see [29] for more details, see also [30]). Therefore, we briefly describe these method and then present our results in Section 2. We end the paper with a discussion of the results in Section 3.

2 Results

In this paper, we calculate a series of binary evolutions with different initial conditions for the WD mass, secondary mass and orbital period. Both the WD + MS and WD + RG channels are included. In an initial binary system, the companion fills its Roche lobe at the MS or during the HG or RG stage, and then the mass transfer occurs. The WD accretes the transferred material from the companion, increasing its mass. Here, we adopt the optically thick wind model suggested by Hachisu et al. [45]. We simultaneously consider the mass-stripping effect by the wind and the effect of a thermally unstable disk [18,38]. When the mass of the WDs reaches $M_{\text{WD}}^{\text{SN}} = 1.378M_{\odot}$ (close to Ch mass limit, [7]), we assume a SN Ia explosion occurs. We subsequently record the state of the companion at the moment of explosion. Now, based on observations, we may deduce various parameters of the potential companion of a SN Ia, such as mass, radius, effective temperature, luminosity, space velocity, rotation velocity, etc. All these parameters may also be obtained from our calculations.

It is important to note, however, that the companion’s parameters obtained at the moment of supernova explosion from our calculations may be different from those found later in a SN Ia remnant because the interaction with the supernova ejecta can change the situation of the companion. During the interaction, the ejecta may strip off some of the hydrogen-rich material from the envelope of the companion. At the same time, the companion gains a kick velocity, which is vertical to the orbital velocity. Part of the kinetic energy of the ejecta is deposited into the envelope of the companion. As a result, the radius and luminosity of the companion will rise dramatically, and the companion may

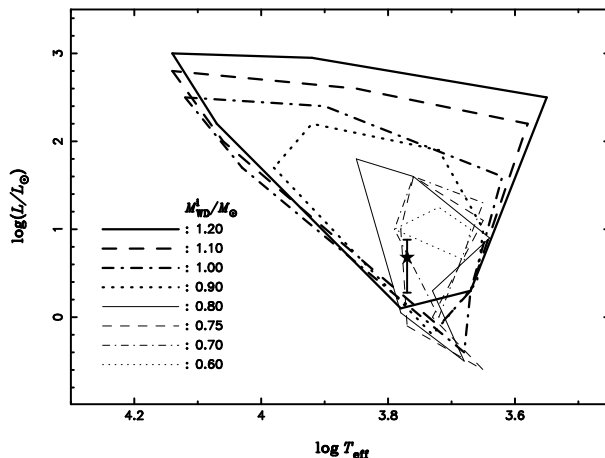


Figure 1: The parameter spaces of luminosity and temperature of the companion at the moment of supernova explosion with different initial WD masses. The star represents the potential companion star of Tycho’s supernova, Tycho G, and the bar represents the observational error [26].

lose dynamic equilibrium. After the interaction, the companion reestablishes dynamic equilibrium quickly while it is still in the process of moving back into thermal equilibrium. This process into thermal equilibrium may last for $10^3 - 10^4$ yr [31-34]. The age of Tycho’s supernova is about 440 yr, which means that the suggested companion star, Tycho G, is still not back into thermal equilibrium if it is the companion star of Tycho’s supernova. Similarly, a companion star is also not in thermal equilibrium at the moment of a supernova explosion since mass transfer is taking place before the explosion. So, considering that the amount of stripped material from the companion is small [35-37], we may assume that the parameters of a companion (such as radius, effective temperature, mass and luminosity) are similar before and after the SN Ia event. The space velocity of the companion may also be assumed to be the same as its orbital velocity since the kick velocity is much smaller than its orbital velocity and as a result may be ignored [31,32,37]. Therefore, our results can be compared directly with observations.

2.1 Luminosity and Effective Temperature of Companion at Explosion

In Figure 1, we present the parameter spaces of luminosity and temperature of the companion at the moment of supernova explosion with different initial WD masses. The range in luminosity is very large and the luminosity may reaches a maximum near $10^3 L_\odot$ since the initial mass of companion is as large as $5 M_\odot$ and the WD+RG channel is also included. In addition, the temperature range is much larger than that shown in Han (2008)[28] since in this paper we considered

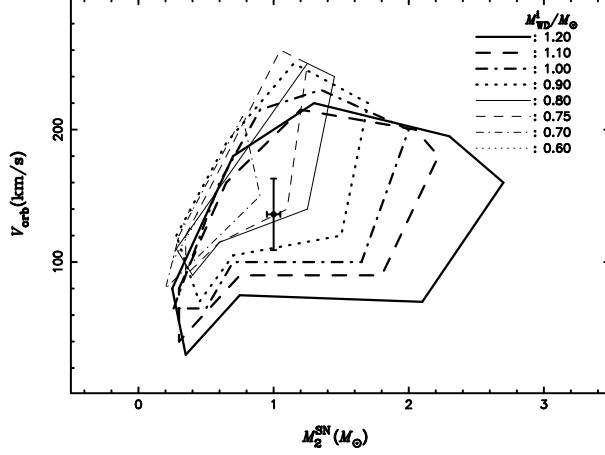


Figure 2: Similar to Figure 1, but for companion mass and orbital velocity. The cross represents Tycho G and the length of the cross shows the typical observational errors, where the velocity of Tycho G here is space velocity [25].

the mass-stripping effect by the optically thick wind and the effect of a thermally unstable disk [18,38]. However, because an initial WD mass of $\sim 0.8M_\odot$ is favored based on detailed binary population synthesis (BPS) results [14,29], most of the companions should be located in the range of $3.7 < \log T_{\text{eff}} < 3.8$ and $0 < \log L < 2$, which is consistent with the BPS results of Han (2008)[28]. Since Han (2008)[28] only investigated the WD+MS channel, the consistent result here implies that the contribution of the WD+RG channel is not as important as the WD+MS channel [13,29], as shown in [29]. The potential companion of Tycho's supernova, Tycho G, is well within the range of highest probability in our range of luminosity and temperature.

2.2 Mass and Space Velocity

Figure 2 shows the parameter spaces of companion mass and orbital velocity for different initial WD masses at the moment of explosion. The ranges of companion mass and orbital velocity here are only slightly larger than those shown in Han (2008)[28] and Meng & Yang (2010) [21] even though we considered the mass-stripping effect by optically thick wind and the effect of a thermally unstable disk which can increase the maximum initial companion mass from $3.5 M_\odot$ to as large as $5 M_\odot$. However, the mass-stripping effect can strip off a large amount of hydrogen-rich material from the envelope of the companion, which may lead to a less massive companion than without the effect at the moment of a SN Ia explosion. For the same reason as in section 2.1, most of the companion stars should be in the range of $0.5M_\odot < M_2^{SN} < 1.4M_\odot$ and $100\text{kms}^{-1} < V_{\text{orb}} < 200\text{kms}^{-1}$, which is also consistent with the BPS results of Han (2008)[28] and Meng & Yang (2010) [21]. It should again be noted that

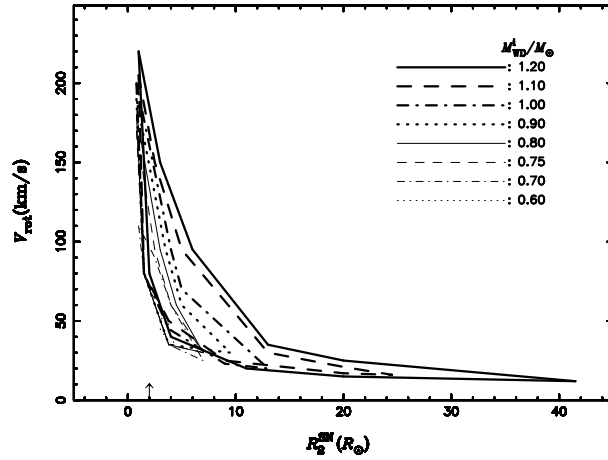


Figure 3: Similar to Figure 1, but for companion radius and equatorial rotational velocity. The arrow represents Tycho G [25,27].

Han (2008)[28] and Meng & Yang (2010) [21] only investigated the WD+MS channel, while in this study we also include the WD+RG channel. The consistent results here mean that the contribution of the WD+RG channel to SNe Ia is small and the number of companions with high initial mass is smaller than that with low initial mass, as shown in [29]. However, it should be emphasized that the WD+RG channel is the main one contributing to very old SNe Ia in early type galaxies and the progenitor systems with massive companion may be the contributor to the young SNe Ia with age younger than 1 Gyr. Tycho G is also located in the parameter space with highest probability. Then, these two parameters of Tycho G are also consistent with the prediction from our model.

2.3 Companion Radius and Rotational Velocity

We calculate the companion radius at the moment of explosion based on the assumption that it is equal to its Roche lobe radius. The equatorial rotation velocity is chosen as the rotational velocity and we assume that the companion star co-rotates with its orbit. In Figure 3, we show the parameter spaces of companion radius and equatorial rotational velocity for different initial WD masses. From the figure, we can see that the rotational velocity of the surviving companions may be as high as 200 km s^{-1} , which means that their spectral lines should be noticeably broadened. In general, a companion star with a large radius has a lower rotational velocity and the rotation rate increases with decreasing radius. The companion stars with radii larger than $10 R_\odot$ are all from the WD+RG channel and have low rotational velocities. We expect companions in early type galaxies to have these properties. The companion stars with radii smaller than $10 R_\odot$ are mainly from the WD+MS channel. For the reason mentioned in section 2.1, most of the companion stars should be in the

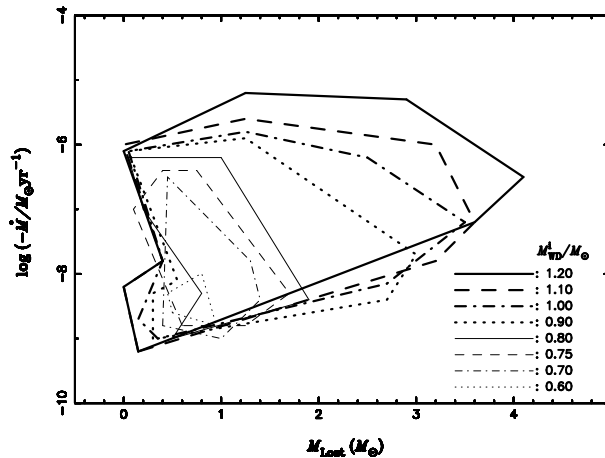


Figure 4: Similar to Figure 1, but for mass-transfer rate at the moment of supernova explosion and the total amount of material lost from the binary system.

vicinity $\sim 100 \text{ km s}^{-1}$ and $\sim 1 R_{\odot}$, which is also consistent with the results of Han (2008)[28] and Meng & Yang (2010) [21]. However, it should be noted that although the radius of Tycho G matches well with our calculation, its rotational velocity is much smaller than that predicted from our model. Actually, this is the reason why Kerzendorf et al. [27]¹ argued the companion nature of Tycho G for Tycho’s supernova (see discussion about this problem).

2.4 Mass Loss

Figure 4 shows the parameter spaces of mass-transfer rate at the moment of supernova explosion and the total amount of material lost from the binary system for different initial WD masses. From the figure, one can see that some binary systems have lost a large amount of material, while their mass-transfer rates are still very high at the moment of supernova explosion, i.e. several times $10^{-6} M_{\odot} \text{ yr}^{-1}$. The SNe Ia originating from these stars may exhibit properties similar to those of SN 2002ic and 2006X [39,40], which may be experiencing an optically thick wind phase before explosion [41]. However, supernovae exploding during this phase are very rare [43]. In addition, there are some systems in which the mass-transfer rates are very low (lower than $10^{-9} M_{\odot} \text{ yr}^{-1}$) and almost no material is lost. The lost material consists of two parts, i.e. the optically thick wind from the surface of the WD and that which is stripped off by the wind from the envelope of the companion. The velocity of the wind is as high as 2000 km s^{-1} , while the velocity of those stripped off from the companion envelope is only about 100 km s^{-1} [18]. The lost material may be the main origin of the color excess of SNe Ia [42]. For most cases, the amount of

¹Note that the rotational velocity of Tycho G was obtained based on an assumption that $\sin i$ (where i is the inclination angle of rotational axis) is closer to 1 than 0.

material lost by the systems is around $1 M_{\odot}$, and mass-transfer rate is around $10^{-8} M_{\odot} \text{yr}^{-1} \sim 10^{-7} M_{\odot} \text{yr}^{-1}$. The results shown here may be helpful in finding progenitor systems before a supernova explosion, in verify the potential progenitor system from archive data after the supernova explosion, or in constraining the X-ray luminosity of a progenitor system candidate. The mass transfer rates can be converted to an X-ray luminosity for the binary system via $L_X \sim \varepsilon |\dot{M}|$, where $\varepsilon = 7 \times 10^{18} \text{ erg g}^{-1}$ is the approximate amount of energy obtained per gram of hydrogen converted into helium. The luminosity of the X-ray source close to the site of SN 2007on was estimated to be $(3.3 \pm 1.5) \times 10^{37} \text{ ergs}^{-1}$ [44]. This luminosity corresponds to a mass accretion rate of $\sim 10^{-7} M_{\odot} \text{yr}^{-1}$, which is consistent with our calculations.

3 Discussion and Conclusion

A good way of discriminating between the many SN Ia progenitor scenarios is to search for the companion of a SN Ia in its remnant. Unless the companion is another WD (DD channel, in which it has been destroyed by the mass-transfer process itself before explosion), it survives and shows some special properties in its spectrum, which originates from the contamination of the supernova ejecta [25,31]. Tycho's supernova, which is one of only two SNe Ia observed in our Galaxy, provides an opportunity to observationally address the identification of the surviving companion. By searching the region of its remnant, a sun-like star, Tycho G, was suggested to be the companion of Tycho's supernova. Chemical abundance analysis of Tycho G upholds its companion nature [26]. Interestingly, some integral properties of Tycho G (the mass, space velocity, radius, luminosity and effective temperature) are all consistent with our computational results, with the exception of the rotational velocity (see also [27]). However, whether the inconsistent result for the rotational velocity is a key factor against for the companion nature of Tycho G still should be investigated more carefully, because the interaction between supernova ejecta and companion star is still unclear. For example, some calculations predicted that there should be a large amount of hydrogen-rich material stripped from the companion envelope by the ejecta in the supernova remnant. This stripped materials may be revealed by narrow H_{α} lines in later-time spectra of SNe Ia [31-33], but this prediction has not been uphold by observations [36,37]. Whether the interaction may change the rotational velocity of the companion star is unclear since the rotational property of the companion has never been considered when simulating the interaction between the supernova ejecta and the companion. For example, because of rotation, the amount of supernova ejecta accreted by the companion on the blue-shift side (rotational velocity is facing the ejecta velocity) could be slightly larger than that on the red-shift side. The small discrimination in angular momentum between the blue- and red-shift side of the companion caused by the different accretion rates may change the rotational dynamics of the companion. If the interaction slows the rotational velocity of the companion, Tycho G is fully explained by the SD model making it an excellent candidate for the companion

Tycho's supernova. Otherwise, the companion nature of Tycho G must be reconsidered. So, more detailed study of Tycho G is encouraged. Furthermore, when one simulates the interaction between supernova ejecta and companion, the rotational property should be considered carefully.

Acknowledgement: *This work was partly supported by the Natural Science Foundation of China (Grant No. 11003003), the Project of Science and Technology from the Ministry of Education (211102) and the China Postdoctoral Science Foundation funded project 20100480222.*

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